



# Spontaneous Heating Liability of Indian Coals: Mechanisms, Susceptibility Assessment, and Mitigation Strategies – A Comprehensive Review

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## Abstract

Spontaneous combustion of coal poses a persistent and severe hazard in underground and opencast mining operations worldwide, with Indian coalfields being particularly vulnerable due to the prevalence of high-volatile bituminous and sub-bituminous coals of Gondwana origin. This comprehensive review synthesizes the mechanisms of spontaneous heating, intrinsic and extrinsic factors influencing susceptibility, laboratory assessment techniques, and protective measures, drawing from extensive studies on coals collected from major Indian coalfields including MCL, BCCL, SCCL, SECL, WCL, and NECL.

Key findings reveal that higher moisture content and volatile matter significantly enhance oxidation propensity, whereas elevated ash content acts as a natural inhibitor by serving as a heat sink and physical barrier. Established laboratory methods such as proximate analysis, Crossing Point Temperature (CPT), Flammability Temperature, Wet Oxidation Potential (WOP), and Mahadevan's Liability Index provide reliable and reproducible indicators of spontaneous heating liability. The review critically evaluates conventional and advanced protective strategies, including stockpile management, inertisation techniques using nitrogen and CO<sub>2</sub>, chemical inhibitors (sodium nitrate, calcium/magnesium chloride, phosphates), and emerging sealing technologies such as gel foams, biomass-derived hydrogels, and three-phase foams.

Special emphasis is placed on integrated approaches that combine real-time gas and temperature monitoring, Computational Fluid Dynamics (CFD) and multiphysics modeling, and site-specific interventions to effectively control the oxidation zone in goaf areas. Challenges in dynamic long-term goaf environments and the need for customized solutions tailored to Indian geological conditions are also highlighted.

This synthesis offers valuable insights for improved risk assessment, proactive fire prevention, and sustainable coal mining practices in India and other regions with similar coal characteristics.



**Keywords:** Spontaneous combustion, Indian coals, Crossing Point Temperature (CPT), Wet Oxidation Potential (WOP), mine fires, inertisation, gel foams, goaf management.

## 1. Introduction

Spontaneous combustion in coal mines remains a critical challenge, as the gradual accumulation of heat from low-temperature oxidation processes frequently culminates in destructive fires (Behera, 2015; Mahananda, 2014). These incidents lead to significant economic losses and environmental degradation while complicating resource extraction and mine safety planning (Sahu, 2014). Furthermore, the release of greenhouse gases from these subterranean fires exacerbates the environmental impact, necessitating precise evaluation methods for coal reactivity to guide effective mitigation strategies (Mohalik et al., 2016). Consequently, assessing the spontaneous heating susceptibility of these coal seams requires a multifaceted investigation into their physico-chemical properties and oxidation kinetics (Lakra, 2011; Onifade & Genc, 2020). Research indicates that while various experimental frameworks—ranging from thermal analysis to gas evolution profiling—exist to predict these liabilities, the absence of a standardized methodology underscores the complexity of the underlying oxidation mechanisms (Onifade & Genc, 2019). Specifically, the auto-oxidation process, characterized by oxygen interaction at ambient temperatures, requires careful monitoring of gas indices such as CO and H<sub>2</sub> to predict potential ignition (Singh, 2013). Beyond these gaseous indicators, advanced thermogravimetric analysis provides a quantitative assessment of mass gain profiles, which serves to correlate proximate coal characteristics with ignition behavior (Mohalik et al., 2021). Furthermore, the application of various chemical inhibitors serves as a strategic intervention to decelerate these oxidation reactions, thereby mitigating the risk of thermal runaway in high-liability coal seams (Kachariya, 2014). Recent laboratory investigations into these chemical interventions have demonstrated that specific aqueous solutions can significantly raise the crossing point temperature of coal, thereby effectively inhibiting its auto-oxidation potential (Mohalik et al., 2018; Ranveer & Udayabhanu, 2026). These inhibitory mechanisms are particularly vital for coalfields in regions such as Singareni and the South Eastern Coalfields, where varying geological and intrinsic seam factors necessitate tailored mitigation protocols (Jena, 2011; Nanda, 2010). Moreover, the integration of advanced kinetic modeling and geothermal activation research reveals that pretreatment of coal at elevated ground temperatures can fundamentally alter reaction barriers, requiring a more nuanced approach to risk assessment in deep-mining operations. Additionally, the classification of coal seams based on intrinsic properties—such as petrographic composition and mineral content—has emerged as a robust alternative to time-consuming experimental indices like crossing point temperatures (Agarwal et al., 2025). By systematically evaluating mass change profiles through thermogravimetric analysis, researchers can derive a 'TG<sub>spc</sub>' index to quantify the spontaneous combustion propensity of coal and coal-shale samples collected from distinct geological seams (Onifade et al., 2020). This analytical framework is complemented by the division of goaf areas into distinct zones based on oxygen concentration gradients, which facilitates the identification of critical regions prone to thermal accumulation (Wei et al., 2020). Furthermore, the application of computational fluid dynamics modeling, specifically regarding air leakage channels, allows for the simulation of temperature fields in these zones, providing critical data on the evolution of combustion areas. These simulations, when integrated with deep learning and real-time gas monitoring, enable the precise prediction of secondary hazards and the optimization of inert gas injection strategies (Simulation, Experiment and Modeling of Coal Fires, 2026), including or carbon dioxide to mitigate oxidation and suppress explosive methane concentrations within the goaf. Additionally, researchers have increasingly integrated multiphysics coupling models to analyze the thermal-fluid-solid interactions during coal deformation, which is essential for understanding gas seepage and its impact on spontaneous combustion. Moreover, recent studies have demonstrated that the heterogeneous nature of gangue-containing coal significantly alters



oxygen consumption rates and activation energy, requiring adjustments to standard kinetic models. Furthermore, incorporating ethylene and ethane as diagnostic indicators enhances the resolution of gas-based self-heating models, bridging the gap between laboratory-scale reaction kinetics and field-scale goaf conditions. Building upon these diagnostic capabilities, the advancement of four-dimensional porosity models further refines the estimation of oxygen availability within the goaf by accounting for the dynamic movement of working faces and resultant pressure gradients (Song et al., 2023). Such predictive frameworks are further bolstered by analyzing representative gas concentrations and temperature variations, which collectively enable the advance identification of high-risk zones and the determination of specific hazard degrees within the goaf. In particular, numerical simulations utilizing the discrete element method have proven instrumental in quantitatively mapping porosity distributions and seepage velocities, thereby optimizing the placement of nitrogen injection ports to minimize fire risk. Recent advancements in field-scale applications have further leveraged these numerical frameworks to characterize three-dimensional hazardous areas, facilitating the precise reconstruction of combustion risk zones. By applying such multi-field coupling models to complex mining environments, operators can define critical thresholds for seepage velocity and oxygen concentration, which are essential for guiding mitigation in U-shaped ventilation systems. Additionally, the creative application of triangular characteristic modeling allows for the simplification of high-temperature zone localization, enabling operators to ascertain critical thermal distributions based on air inlet parameters. Furthermore, the implementation of multi-physical field coupling models that integrate gas seepage, diffusion, and heat conduction has become essential for identifying composite hazard zones in gob areas. These integrated analytical approaches are further refined by classifying spontaneous combustion risk into distinct regions, such as the rear sections of working faces and gob-side entry areas, where leakage through flexible formwork walls necessitates specialized containment strategies. In these environments, variations in goaf porosity significantly influence airflow velocity and oxygen distribution, directly dictating the extent of the oxidized zone. Specifically, numerical simulations have established that the "spontaneous combustion zones" expand vertically with height, leading to larger risk areas that require robust monitoring protocols. Consequently, coordinating gas drainage flow in high-drainage roadways with localized fracture sealing is vital to decoupling gas accumulation from thermal runaway in these interconnected zones. Furthermore, optimizing nitrogen injection protocols involves precise calibration of discharge rates and nozzle positioning relative to these identified high-leakage conduits, which significantly enhances fire prevention efficiency (Wang & Liu, 2025). For instance, investigations have demonstrated that the effectiveness of these measures depends heavily on the spatial positioning of the injection ports; placing them approximately 30 meters from the working face, coupled with optimized flow rates, has been shown to minimize the width of the oxidation zone. Beyond static placement, dynamic adjustment of injection rates ensures that nitrogen concentrations remain effective even as goaf airflow conditions fluctuate due to roof movement and pressure relief. Moreover, the introduction of innovative techniques, such as full cross-section nitrogen curtains, has demonstrated superior efficacy in achieving homogeneous gas diffusion within U-shaped ventilation systems, effectively reducing the maximum width of the oxidation zone (Geng et al., 2023). Moreover, adopting separated nitrogen injection technologies facilitates more effective inertization in wide working faces by addressing the limitations of conventional single-pipe systems. By systematically analyzing the "three-zone" distribution through bundle tube monitoring and numerical simulation, operators can determine the optimal nitrogen injection volume required to decrease oxygen concentrations below the threshold for thermal runaway, thereby establishing a proactive barrier that restricts oxidation in the goaf. Furthermore, field data indicate that maintaining a rational nitrogen injection rate—typically between 660 and 800 m<sup>3</sup>/h—is essential for effectively reducing the maximum width of the oxidation zone in fully mechanized caving faces. Beyond simple injection volumes, integrating low-temperature nitrogen



application with strategic corner grouting and air leakage sealing further enhances the integrity of fire prevention during equipment withdrawal periods. Specifically, the implementation of standardized nitrogen injection procedures during these phases has proven vital for suppressing spontaneous combustion phenomena and mitigating potential fire accident losses in mechanized working faces (Ming-guo, 2012). Recent research further emphasizes that, in complex geological settings, the simultaneous application of high-position borehole extraction and floor-level drainage, while effective for gas mitigation, requires compensatory nitrogen injection to prevent the undesirable expansion of the oxidation zone induced by stereoscopic suction. Furthermore, the implementation of non-interval, rotating traction injection techniques allows for continuous, synchronous movement with the advancing face, thereby overcoming the spatial limitations of traditional buried tube systems (Shi-liang, 2013). This approach leverages laser beam tube monitoring to facilitate real-time gas analysis and automated calibration, enabling instantaneous transmission of data to ground-level dispatch centers for precise intervention. In addition, the integration of 3D numerical simulation tools, such as the Fluent software package, has proven essential for visualizing complex oxygen concentration and temperature fields within the residual coal mass. These computational insights allow for the proactive identification of unpredictable air leakage passages, which are often difficult to characterize through traditional field measurements alone. Moreover, such predictive modeling enables the mitigation of coupled disaster risks by identifying optimal gas and fire control parameters specifically during sensitive mining withdrawal stages.

Recent studies have highlighted the increasing importance of integrating advanced monitoring technologies, risk assessment methodologies, and sustainable mining practices into spontaneous combustion management systems. Artificial intelligence-based approaches have shown considerable potential for improving hazard prediction and early warning systems in mining environments (Gopal Singh et al., 2024). Similarly, comprehensive risk assessment frameworks and safety management practices have been recognized as essential tools for minimizing fire hazards and improving operational safety in underground coal mines (Gopal Singh et al., 2025; Bisen & Chaurasia, 2026). The interaction between coal seam characteristics, methane occurrence, and hydrocarbon generation potential further influences spontaneous heating behaviour, emphasizing the need for integrated coal characterization and gas monitoring studies (Panwar et al., 2017; Panwar et al., 2019; Panwar et al., 2021; Panwar et al., 2022; Nath et al., 2023a; Nath et al., 2023b; Singh et al., 2025). Furthermore, recent reviews on coal mining practices, environmental impacts, occupational health and safety, and sustainable mining have stressed the necessity of adopting holistic fire prevention strategies that combine technological innovation, environmental stewardship, and operational risk management (Yadav & Chaurasia, 2025a; Yadav & Chaurasia, 2025b; Yadav & Chaurasia, 2025c; Mansoori & Chaurasia, 2025). Advances in coal characterization, beneficiation, and clean coal technologies have also provided valuable insights into the intrinsic properties governing coal oxidation and spontaneous combustion susceptibility (Chaurasia & Nikkam, 2016a; Chaurasia & Nikkam, 2016b; Sahu et al., 2018; Chaurasia et al., 2018). In addition, sustainable mine management practices, including mine closure planning, mine waste utilization, and environmental monitoring, contribute significantly to reducing long-term fire risks and environmental impacts associated with coal mining operations (Bisen et al., 2025; Chourasiya & Chaurasia, 2026a; Chourasiya & Chaurasia, 2026b). These developments collectively demonstrate the growing trend toward integrated, data-driven, and sustainable approaches for assessing and mitigating spontaneous combustion hazards in coal mines.

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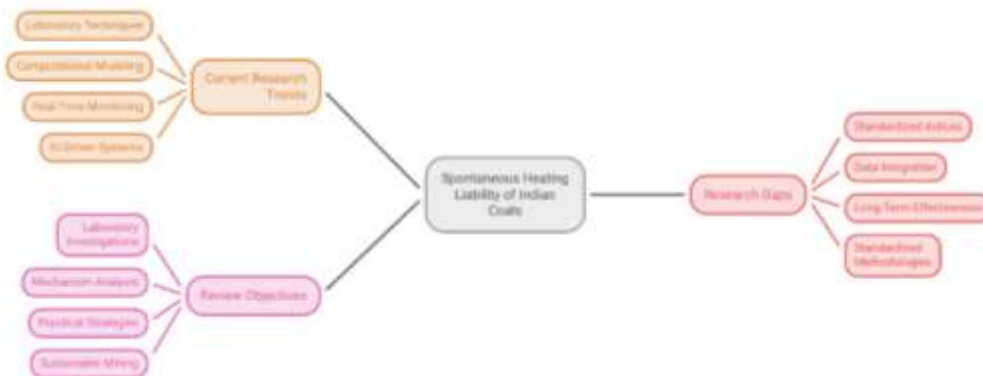


Fig.1. Spontaneous heating liability of Indian coal: trends and research gaps

This review addresses these challenges by synthesizing detailed laboratory investigations on Indian coals with critical analysis of mechanisms, susceptibility factors, assessment methodologies, and field-proven protective measures. It bridges the gap between experimental findings (including CPT-WOP correlations with proximate properties) and practical mine management strategies, providing actionable recommendations for risk assessment, prevention, and mitigation tailored to Indian conditions. The work aims to support the development of more effective, integrated fire prevention frameworks for sustainable coal mining operations.

### Mechanism of Spontaneous Heating

Spontaneous heating is a self-sustaining low-temperature oxidation process initiated when coal reacts with atmospheric oxygen. The reaction generates heat through the formation of coal-oxygen complexes (peroxides and hydroperoxides), which decompose exothermically. If the rate of heat generation exceeds the rate of heat dissipation through conduction, convection, or radiation, the temperature within the coal mass rises progressively, eventually leading to thermal runaway and ignition.

The overall process is heterogeneous, occurring at the solid-gas interface, and is highly time-dependent. Coal, being a complex mixture of organic macerals and mineral matter, undergoes multiple overlapping reactions. The phenomenon is best understood through the coal-oxygen complex theory, which describes the formation and decomposition of unstable oxygenated compounds that regenerate fresh reactive sites, creating an autocatalytic cycle. The spontaneous combustion process is typically divided into three distinct temperature-dependent phases:

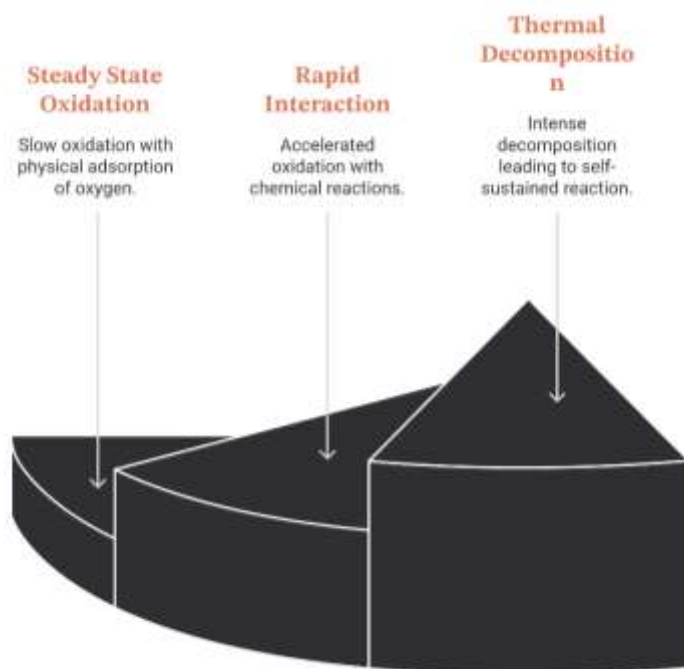


Fig.2. Coal oxidation stages

**Phase I: Steady State Oxidation (50–80°C)** In the initial incubation stage, coal undergoes slow oxidation dominated by physical adsorption of oxygen on its surface. Moisture removal occurs, and the heat generated is largely dissipated to the surroundings. The process remains relatively stable with minimal chemical transformation, making early detection challenging.

**Phase II: Rapid Interaction with Oxygen (80–180°C)** As the temperature rises above 80°C, the oxidation rate accelerates significantly. The transition from physical adsorption to chemical reaction takes place, leading to the formation of more stable oxygenated compounds. Carbon monoxide evolution becomes noticeable around 120°C, serving as a key early warning indicator. This phase is critical because the self-heating process becomes self-accelerating.

**Phase III: Thermal Decomposition and Self-Sustained Reaction (>180°C)** Beyond 180°C, thermal decomposition intensifies. The coal structure breaks down, releasing volatile matter and accelerating exothermic reactions. Once the temperature reaches approximately 220–275°C, the process becomes self-sustained, culminating in open-flame ignition.

The primary chemical reactions responsible for heat generation during spontaneous heating are as follows:



These reactions highlight the intrinsic heterogeneous nature of the process. The incomplete combustion reaction producing CO is particularly significant in oxygen-limited environments such as goaf areas.



## Characteristics of Indian Coals

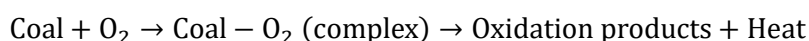
Indian coals, predominantly of Gondwana origin, are characterized by high ash content and relatively high moisture levels compared to Carboniferous coals of the Northern Hemisphere. These properties result in distinct oxidation kinetics. High ash acts as a heat sink and physical barrier, generally reducing spontaneous heating propensity, while high volatile matter and reactive functional groups increase susceptibility, especially in lower-rank (sub-bituminous to high-volatile bituminous) coals.

## Major Supporting Theories

Several theories have been proposed over the decades to explain the phenomenon of spontaneous heating of coal. While no single theory can fully account for all aspects of the process, each contributes valuable insights. The following theories are particularly relevant in the context of Indian coals.

### Coal-Oxygen Complex (Phenol) Theory

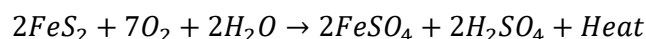
The Coal-Oxygen Complex Theory, also known as the Phenol Theory, is the most widely accepted modern explanation for spontaneous combustion. It proposes that coal contains phenolic and other reactive functional groups (such as hydroxyl, carboxyl, and carbonyl) that readily combine with atmospheric oxygen at low temperatures to form unstable coal-oxygen complexes (peroxides and hydroperoxides). These complexes subsequently decompose exothermically, releasing heat and regenerating fresh active sites. This creates an autocatalytic cycle that accelerates the oxidation process:



The autocatalytic nature explains why the reaction rate increases progressively once initiated, eventually leading to thermal runaway. This theory best aligns with the observed behavior of Indian coals.

### Pyrite Theory

The Pyrite Theory highlights the catalytic role of pyrite ( $\text{FeS}_2$ ), which is commonly present in many coal seams. The oxidation of pyrite is highly exothermic and produces heat, sulfuric acid, and ferric sulfate, which further accelerate the oxidation of the surrounding coal matrix. The key reaction is:



This theory is especially relevant for coals with pyritic sulfur content greater than 1–2%. In Indian coals, where pyrite is often finely disseminated, this mechanism can significantly lower the threshold for spontaneous ignition.

### Moisture (Humidity) Theory

Moisture plays a dual and critical role in spontaneous heating. At moderate levels, it promotes oxidation through the heat of wetting (exothermic absorption of moisture by dry coal). However, high moisture can temporarily suppress heating due to evaporative cooling. Repeated wetting-drying cycles cause cracking of coal particles, increasing surface area and exposing new reactive sites. This theory explains why many Indian coals with 8–15% moisture are particularly susceptible under fluctuating climatic conditions.

### Heat Accumulation Theory

This is an integrative theory that combines elements of all the above. It emphasizes that spontaneous combustion occurs only when the rate of heat generation exceeds the rate of heat dissipation through conduction, convection, or radiation. Factors such as poor ventilation, large coal mass, pile geometry,

and insulation by surrounding strata determine whether the self-heating process will progress to ignition.

### Factors Influencing Spontaneous Heating Liability

Susceptibility to spontaneous heating arises from the complex interplay between intrinsic factors (inherent properties of the coal itself) and extrinsic factors (external environmental, operational, and geological conditions). Understanding these factors is essential for accurate risk assessment, prediction, and development of effective prevention strategies in Indian coal mines.

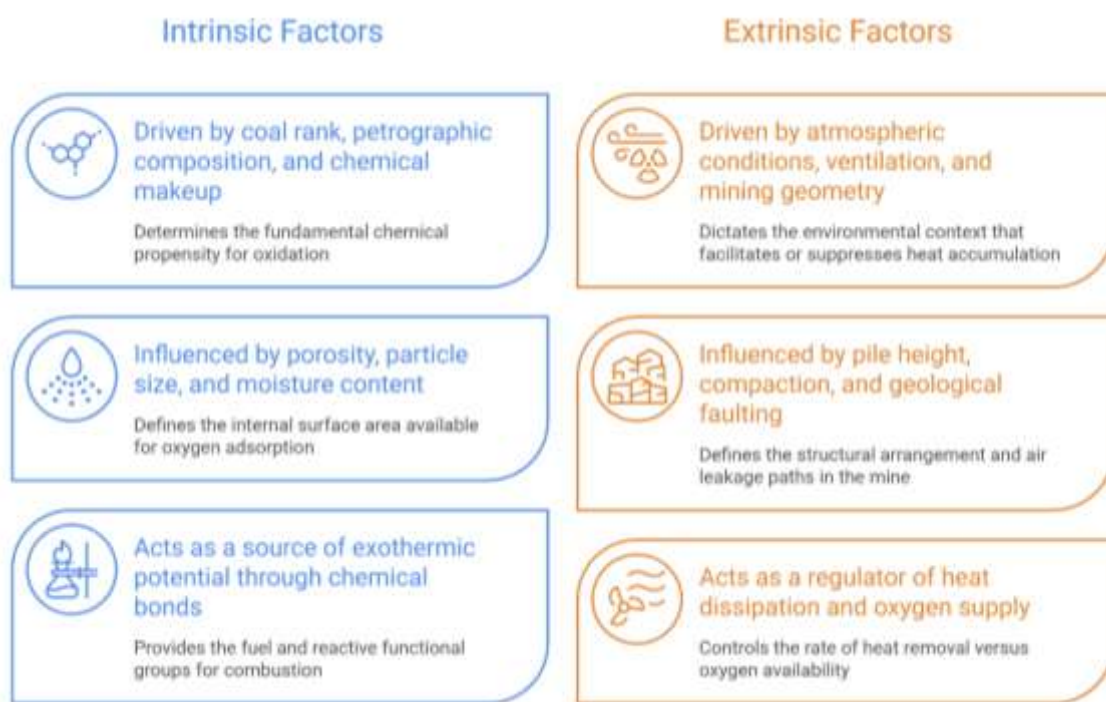


Fig.3. Factors primarily dictates the spontaneous heating liability of coal

#### Intrinsic Factors:

##### Coal Rank and Petrographic Composition

Coal rank is one of the most critical intrinsic factors. Lower-rank coals (lignite and sub-bituminous) exhibit significantly higher propensity for spontaneous heating compared to higher-rank bituminous and anthracite coals. This is primarily due to their higher volatile matter (VM), oxygen content, and greater porosity, which facilitate oxygen adsorption and oxidation. As rank increases, fixed carbon content rises while moisture and VM decrease, thereby reducing reactivity. In the studied Indian coals with GCV ranging from 3800–6200 kcal/kg, many fall into medium-to-low rank categories that are particularly prone to self-heating. Petrographic constituents, including macerals such as vitrinite, liptinite, and inertinite, also play a vital role. Vitrinite-rich coals tend to be more reactive due to their aromatic structure and higher concentration of oxygen-containing functional groups. Liptinite contributes to elevated VM, further enhancing oxidation potential, whereas inertinite is relatively inert.

##### Moisture Content

Moisture plays a dual and complex role in spontaneous heating. Equilibrium moisture affects the heat of wetting a significant exothermic process when dry coal absorbs moisture from humid air. This can initiate or accelerate heating, especially in low-rank coals. Conversely, excessive moisture can act as a



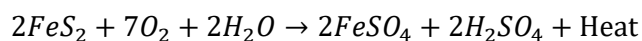
heat sink through evaporation, temporarily suppressing temperature rise. However, repeated cycles of wetting and drying, common in stockpiles and exposed seams, promote cracking and increase reactive surface area, thereby exacerbating oxidation. Indian coals with 10–15% moisture are particularly susceptible to this phenomenon.

### **Volatile Matter and Chemical Composition**

Higher volatile matter content provides more reactive hydrocarbons and functional groups (e.g., hydroxyl, carboxyl, and phenolic groups) that readily oxidize at low temperatures. Proximate and ultimate analyses reveal that coals with elevated hydrogen and oxygen content often show lower Crossing Point Temperature (CPT) and higher Liability Index values. The presence of specific organic structures makes the coal more prone to forming coal-oxygen complexes.

### **Ash Content and Pyrite (FeS<sub>2</sub>)**

Ash generally inhibits spontaneous heating by acting as a heat sink and physical barrier that reduces oxygen access to reactive carbon. However, certain minerals within the ash can catalyze reactions. Pyrite is a major catalyst for spontaneous combustion. Its oxidation is highly exothermic and moisture-dependent:



Coals with >1–2% pyritic sulfur are notably more prone to heating, especially when pyrite is finely disseminated.

### **Particle Size, Surface Area, and Porosity**

Smaller particle sizes dramatically increase specific surface area, enhancing oxygen access and reaction rates. Fine particles (<0.5 mm) can heat faster than larger lumps, although optimal heating often occurs in mixed sizes where fines fill voids, reducing ventilation while retaining heat. Higher porosity and permeability, characteristic of lower-rank coals, allow greater oxygen diffusion into the particle interior, sustaining oxidation over longer periods.

### **Extrinsic Factors:**

#### **Atmospheric and Climatic Conditions**

Ambient temperature, humidity, and rainfall significantly influence oxidation kinetics. Reaction rates roughly double for every 10°C rise in temperature (following Arrhenius behavior). High humidity can trigger heat of wetting, while seasonal variations and diurnal temperature fluctuations are particularly influential in open stockpiles.

#### **Ventilation and Airflow**

Oxygen supply is essential for oxidation, but airflow also dissipates heat. Low airflow rates (insufficient for cooling but adequate for oxygen supply) create ideal conditions for heat accumulation. In goaf areas, this leads to the formation of dangerous oxidation zones.

#### **Storage, Pile Geometry, and Mining Methods**

Stockpile height, compaction, and segregation affect air ingress. Tall, loosely compacted piles promote chimney effects. Mining practices such as slow advance rates in longwall faces, bord-and-pillar methods, and poor goaf management leave residual coal exposed for extended periods, significantly increasing risk.

## Geological Factors

Seam thickness, gradient, faulting, depth, and geothermal gradient further modulate susceptibility. Thick seams and faulted zones create complex air leakage paths and heat accumulation zones.

The most dangerous scenarios emerge from synergistic interactions between these intrinsic and extrinsic factors. For example, high-VM, low-rank coal stored in poorly compacted piles under warm, humid conditions can rapidly progress toward thermal runaway. Comprehensive risk assessment integrating both categories of factors is therefore crucial for Indian coal mines.

## Laboratory Assessment Techniques

Reliable evaluation of spontaneous heating liability is essential for risk classification and the implementation of preventive strategies. Laboratory techniques provide quantitative and reproducible measures that correlate intrinsic coal properties with oxidation behavior. In this study, ten coal samples collected from major Indian coalfields (MCL, BCCL, SCCL, SECL, WCL, and NECL) were subjected to a comprehensive suite of standardized tests. Samples were collected using channel and bulk sampling methods as per Indian Standards (IS:436) from freshly exposed faces to ensure representativeness and minimize pre-oxidation. They were then crushed, sieved to specific particle sizes, and stored under controlled conditions.

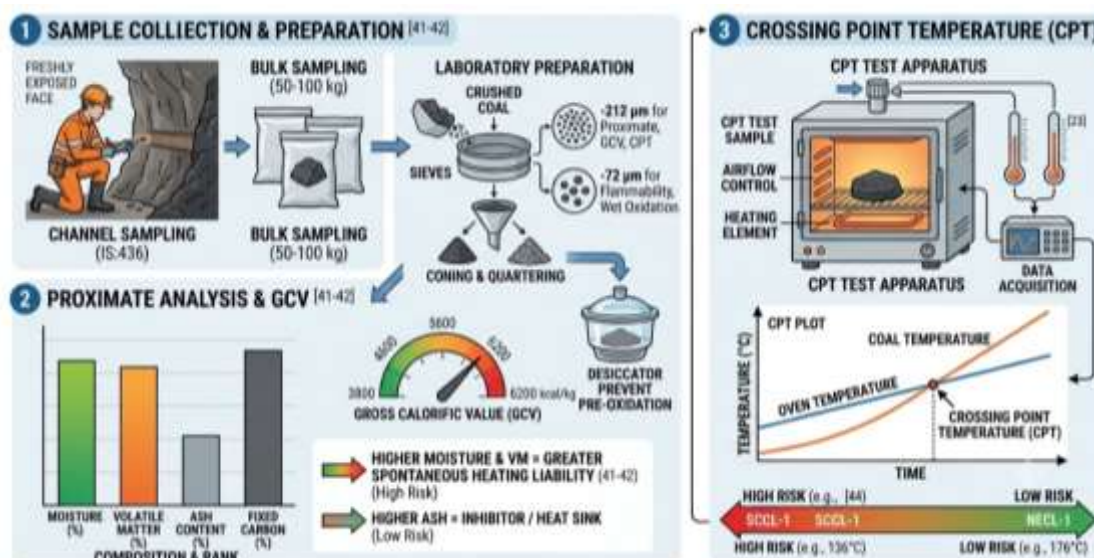


Fig. 4. Laboratory assessment techniques for coal spontaneous heating liability

**Sample Collection and Preparation** Coal samples were collected using channel sampling and bulk sampling methods as per Indian Standards (IS: 436) from freshly exposed faces to ensure representativeness and minimize pre-oxidation. Approximately 50–100 kg of coal was collected from each location and immediately sealed in airtight bags. In the laboratory, samples were homogenized through coning and quartering, crushed, and sieved to required particle sizes. Different fractions were used for different tests:  $-212\ \mu\text{m}$  for proximate analysis, GCV, and CPT; and  $-72\ \mu\text{m}$  for flammability temperature and wet oxidation studies. Special care was taken to store samples in desiccators to prevent atmospheric oxidation prior to testing.

**Proximate Analysis and Gross Calorific Value (GCV)** Proximate analysis determined the percentage of moisture, volatile matter (VM), ash, and fixed carbon (by difference) in the coal samples. These parameters provide fundamental information about coal composition and rank. The Gross Calorific Value (GCV) of the studied coals ranged from 3800 to 6200 kcal/kg, indicating medium to low-rank coals.



Results consistently showed that coals with higher moisture and volatile matter content exhibited greater spontaneous heating liability, while higher ash content acted as an inhibitor by serving as a heat sink and physical barrier to oxygen diffusion.

**Crossing Point Temperature (CPT)** The Crossing Point Temperature (CPT) test is one of the most widely used and reliable methods for evaluating spontaneous heating susceptibility. In this test, a coal sample is placed in an oven with controlled airflow and heated at a constant rate. The CPT is recorded as the temperature at which the coal's self-heating rate exceeds the oven's heating rate. Lower CPT values indicate higher spontaneous heating tendency. In the present investigation, CPT values ranged from 136°C (SCCL-1) to 176°C (NECL-1). Coals from SCCL and BCCL showed the lowest CPT values, confirming their very high risk, while NECL coals recorded the highest CPT, indicating lower susceptibility.

**Flammability Temperature and Wet Oxidation Potential (WOP)** Flammability temperature determines the lowest temperature at which the coal sample ignites under standardized heating conditions, providing insight into the transition from self-heating to actual combustion. Wet Oxidation Potential (WOP), also expressed in terms of activation energy ( $\Delta E$ ), measures the oxidation behavior of coal in an aqueous medium using strong oxidizing agents. This method is relatively quick and serves as a useful complementary index for rapid screening. Both parameters showed strong correlations with proximate analysis results, with higher moisture and VM coals displaying greater oxidation potential.

These laboratory techniques, when used together with Mahadevan's Liability Index and WITS-EHAS classification, provided a robust framework for predictive risk ranking. Strong statistical correlations were observed, particularly a high positive correlation between CPT and ash content ( $R^2 \approx 0.94$ ) and negative correlations with volatile matter and moisture. The integrated assessment clearly differentiated high-risk coals (SCCL and BCCL) from moderate and low-risk coals, offering valuable inputs for mine planning and implementation of suitable protective measures.

### **Protective and Preventive Measures**

Effective mitigation of spontaneous heating in coal mines requires a multi-layered approach that integrates operational practices, engineering controls, and advanced technologies. Preventive strategies aim to either reduce oxygen availability, enhance heat dissipation, inhibit chemical reactions, or enable early detection before thermal runaway occurs. Based on laboratory findings and field observations from Indian coalfields, the following measures have proven effective when applied in a site-specific and integrated manner.

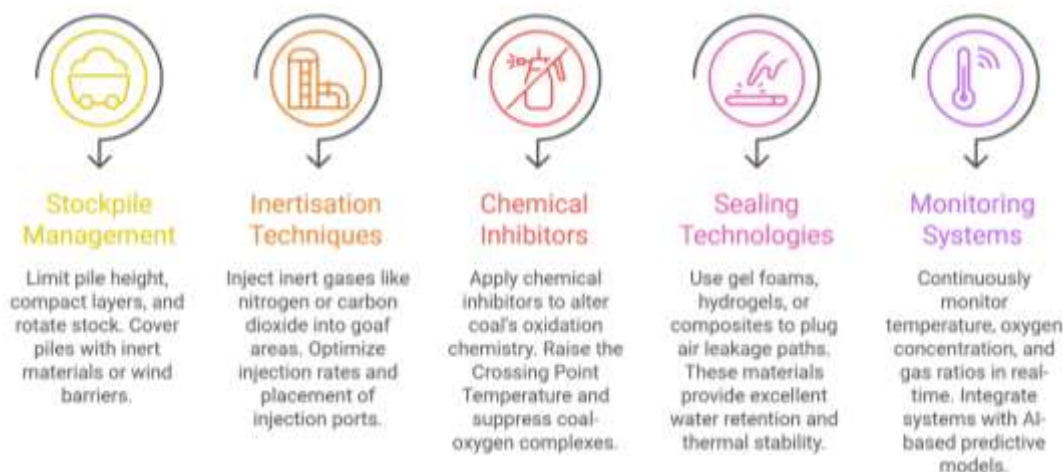


Fig. 5. Coal mines safety Measures  
Stockpile and Mine Management

Proper stockpile management is one of the most practical and cost-effective preventive measures. Key practices include limiting pile height to less than 10–15 meters, compacting layers during stacking to reduce air voids, and implementing regular stock rotation to avoid long-term aging. Covering piles with inert materials or using wind barriers minimizes air ingress and heat buildup. In underground mines, controlled ventilation, rapid face advance rates, and effective goaf compaction help limit oxygen supply to residual coal. These operational controls are particularly important for high-risk coals from SCCL and BCCL, where freshly mined high-volatile coal is highly reactive.

#### Inertisation Techniques

Inertisation involves injecting inert gases such as nitrogen ( $N_2$ ) or carbon dioxide ( $CO_2$ ) into goaf areas to reduce oxygen concentration below the critical threshold (typically <5–8%). Optimized injection rates of 660–800  $m^3/h$  have been shown to effectively shrink the oxidation zone in the three-zone goaf model. Strategic placement of injection ports (often 30 meters behind the face), dynamic adjustment of flow rates, and coupling with gas drainage systems significantly enhance efficacy. Computational Fluid Dynamics (CFD) modeling and three-dimensional porosity simulations are widely used to optimize injection parameters and predict zone behavior. This technique is especially valuable for long-term goaf management and in thick-seam Indian mining conditions.

#### Chemical Inhibitors

Chemical inhibitors are applied to alter the oxidation chemistry of coal. Common inhibitors such as sodium nitrate, calcium chloride, magnesium chloride, and various phosphates raise the Crossing Point Temperature (CPT) and suppress the formation of coal-oxygen complexes. These solutions can be sprayed on coal surfaces in stockpiles or injected into seams. Laboratory studies have demonstrated that specific aqueous inhibitors can significantly delay the onset of self-heating. The selection of inhibitors should be based on coal rank and mineral composition for maximum effectiveness.

#### Advanced Sealing Technologies

Recent advancements in material science have introduced highly effective sealing agents. Gel foams, biomass-derived hydrogels, polyacrylamide-based composites, and fly ash-incorporated three-phase foams offer superior performance in plugging air leakage paths. These materials provide excellent water retention, high viscosity, self-healing properties, and thermal stability even at elevated temperatures. They create strong oxygen barriers within fractures and porous goaf zones. Dual-network and nano-reinforced gels have shown oxidation potential reduction of up to 40% in laboratory tests. Such



technologies are particularly promising for sealing complex leakage channels in Indian coalfields with high fracture density.

### Monitoring and Early Warning Systems

Continuous real-time monitoring is crucial for early detection. Bundle tube sampling, thermocouples, infrared imaging, and gas sensors for CO, hydrocarbons, ethylene, and ethane enable timely intervention. Integration of these systems with AI-based predictive models and multiphysics simulations (DEM-CFD) allows accurate mapping of the three zones in goaf areas and forecasting of high-risk zones. Regular monitoring of oxygen concentration, temperature, and gas ratios provides actionable data for adjusting inertisation and sealing strategies.

Field and laboratory evaluations confirm that integrated strategies combining stockpile management, inertisation, chemical inhibitors, advanced sealing materials, and robust monitoring systems yield the best results. For Indian geological conditions characterized by high-ash, high-moisture coals and complex goaf behavior a tailored, multidisciplinary approach is essential to minimize spontaneous combustion incidents, reduce economic losses, and enhance mine safety. Continued research into cost-effective, eco-friendly inhibitors and real-time digital monitoring will further strengthen these preventive frameworks.

### Discussion and Future Directions

Indian coals, predominantly of Gondwana origin, possess unique physico-chemical characteristics such as high ash content, relatively high inherent moisture, and variable volatile matter that distinguish them from Carboniferous coals of the Northern Hemisphere. These properties necessitate customized approaches for spontaneous combustion risk assessment and mitigation that go beyond generic international frameworks. While laboratory indices like Crossing Point Temperature (CPT) and Wet Oxidation Potential (WOP) show strong correlations with intrinsic properties such as moisture, volatile matter, and ash content, their standalone application has limitations in real-world scenarios. Integrating these indices with site-specific geological data (seam thickness, faulting, geothermal gradient), mining conditions (longwall advance rate, goaf compaction), and advanced numerical modeling significantly improves predictive accuracy and enables more reliable risk zoning.

A major challenge persists in dynamic goaf environments, particularly in long-term goaf areas. Air leakage through evolving fracture networks, changing porosity and permeability due to roof subsidence and compaction, and the heterogeneous distribution of residual coal create complex conditions where the boundaries of the three zones (heat dissipation, oxidation, and asphyxiation) continuously shift. These factors often lead to unpredictable re-activation of oxidation even after initial inertisation, making sustained control difficult in Indian thick-seam and multiple-seam mining operations. Furthermore, the dual role of moisture and the catalytic effect of pyrite add layers of complexity that standard laboratory tests alone cannot fully capture under varying field ventilation and climatic conditions.

Emerging trends in spontaneous combustion research offer promising solutions. Artificial Intelligence (AI) and machine learning-based predictive systems are increasingly being integrated with real-time sensor data (CO, hydrocarbons, temperature, and oxygen) for early warning and dynamic risk forecasting. Nano-scale oxidation studies are providing deeper insights into the formation and decomposition mechanisms of coal-oxygen complexes at the molecular level. Additionally, there is a growing focus on sustainable, eco-friendly bio-based inhibitors and hydrogels derived from biomass, chitosan, and natural polymers, which offer cost-effective and environmentally benign alternatives to traditional chemical treatments.



Future research should prioritize several key areas to bridge existing gaps. Large-scale field validation of advanced gel foam and hydrogel technologies is essential to evaluate their long-term performance, injection feasibility, and economic viability under Indian geological conditions. Development of hybrid inerting-monitoring protocols that combine automated nitrogen injection with AI-driven decision support systems could significantly enhance real-time control of the oxidation zone. Multiphysics modeling incorporating thermal-fluid-solid interactions, dynamic porosity evolution, and machine learning should be further refined for more accurate prediction of spontaneous combustion in long-term goaf. Moreover, studies on the synergistic effects of blending high-risk and high-ash coals, along with the application of nano-reinforced materials, could optimize both safety and resource recovery. Addressing these research needs will be crucial for minimizing spontaneous combustion incidents, reducing greenhouse gas emissions, and promoting safer and more sustainable coal mining operations in India.

## Conclusion

Spontaneous heating remains one of the most persistent and challenging hazards in Indian coal mining, driven by the unique characteristics of Gondwana-origin coals with high volatile matter, moisture, and variable ash content. This comprehensive review has systematically examined the underlying mechanisms of spontaneous combustion, key influencing intrinsic and extrinsic factors, reliable laboratory assessment techniques (particularly CPT, WOP, and proximate analysis), and a wide range of protective and preventive measures. The findings clearly demonstrate that coals from SCCL and BCCL exhibit higher susceptibility, while ash-rich coals from NECL and WCL show relatively lower risk, validating strong correlations between coal properties and spontaneous heating indices.

By leveraging fundamental proximate properties, Crossing Point Temperature (CPT), Wet Oxidation Potential (WOP), and advanced tools such as Mahadevan's Liability Index, accurate risk ranking and prediction are achievable. When combined with multifaceted prevention strategies — including optimized stockpile management, nitrogen/CO<sub>2</sub> inertisation, chemical inhibitors, advanced gel foams and hydrogels, and real-time monitoring systems — significant reductions in spontaneous combustion incidents can be realized. The integration of numerical modeling (CFD and multiphysics) with field practices further strengthens the ability to control the oxidation zone in both active and long-term goaf areas.

This review underscores the urgent need for proactive, integrated, and site-specific fire management frameworks tailored to Indian geological and mining conditions. Adoption of such holistic approaches will not only enhance mine safety and reduce economic losses but also minimize environmental impacts through lower greenhouse gas emissions and better resource conservation. Ultimately, sustained collaboration between researchers, mine operators, and policymakers, supported by emerging technologies like AI-driven prediction and sustainable bio-based inhibitors, will be instrumental in achieving safer and more sustainable coal mining operations across India.

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